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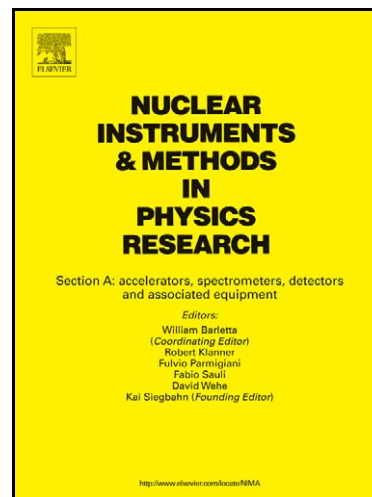
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The X-ray Quantum Efficiency Measurement of High Resistivity CCDs

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Abstract

The CCD247 is the second generation of high resistivity device to be manufactured in e2v technologies plc development programme. Intended for infrared astronomy, the latest devices are fabricated on high resistivity ($\sim 8 \text{ k}\Omega\text{-cm}$) bulk silicon, allowing for a greater device thickness whilst maintaining full depletion when 'thinned' to a thickness of $150 \mu\text{m}$. In the case of the front illuminated variant, depletion of up to $300 \mu\text{m}$ is achievable by applying a gate to substrate potential of up to 120 V, whilst retaining adequate spectral performance. The increased depletion depth of high resistivity CCDs greatly improves the quantum efficiency (QE) for incident X-ray photons of energies above 5 keV, making such a device beneficial in future X-ray astronomy missions and other applications. Here we describe the experimental setup and present results of X-ray QE measurements taken in the energy range 2 keV to 20 keV for a front illuminated CCD247, showing QE in excess of 80% @ 10 keV. Results for the first generation CCD217 and swept-charge device ($1,500 \Omega\text{-cm}$ epitaxial silicon) are also presented.

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Keywords: X-ray; CCD; SCD; quantum efficiency; QE; full depletion; deep depletion; high resistivity; high-rho; SiLi;

1. Introduction

The X-ray QE of a CCD is the percentage of incident photons that are converted into electron-hole pairs and

sampled by the device. This is practically measured for a range of incident photon energies to determine the X-ray sensitivity of the CCD by comparing the flux measured by the CCD at specific energies to that of a calibrated reference detector illuminated by the same source. The relative difference between the flux measured by the CCD and the calibrated detector is used to ascertain the absolute X-ray CCD QE.

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The CCD247 is the second generation of high resistivity device manufactured by e2v technologies plc, intended to provide 150 μm fully depleted, back-illuminated, large area sensors for near infra-red astronomy. Based on the design of the popular 2k \times 4k pixel format, e.g. the CCD42 [1], the starting bulk silicon is of a far higher resistivity ($\sim 8 \text{ k}\Omega\text{-cm}$) than that of standard CCDs (20 to 1,500 $\Omega\text{-cm}$) allowing for a greater depletion depth into the p-substrate region. The depletion depth can be extended further by increasing (negatively) the substrate potential [2]. The depletion depth of epitaxial devices is constrained to the thickness of the epi-layer; bulk material can potentially allow wafer thick depletion ($\sim 600 \mu\text{m}$). The increased bulk resistivity of the CCD247 and redesigned output circuit allows for an applied gate to substrate potential of up to 110 V, whilst maintaining a $<5 \text{ e}^-$ system noise, giving a depletion depth of approximately 300 μm for 'un-thinned' devices [3].

The increased depletion depth of high resistivity CCDs not only improves red-response but greatly improves the quantum efficiency (QE) for X-ray photons of energies above 5 keV; making such technology beneficial to future MOS CCD based X-ray astronomy missions and other applications.

The X-ray sensitivity of a CCD is evaluated by measuring the quantum efficiency (QE) at a range of incident photon energies. This is achieved practically by measuring the relative difference in flux measurements between the CCD and a reference detector when illuminated by the same X-ray source. Ensuring an identical source illumination for both the CCD and reference detector is not possible to achieve practically as both CCD and reference detector cannot occupy the same position at the same time. The following method was therefore devised to move the entire X-ray source between detectors to ensure identical spatial displacement of the detectors allowing flux measurements to be taken with minimal latency between each detector's measurements.

2. Experimental Setup

In order to measure the increased high energy X-ray QE of deep depletion CCDs a reference detector with high QE in the energy range 5 keV to 20 keV was required. A lithium drifted silicon crystal (SiLi) detector was chosen, depleted to $\sim 4.5 \text{ mm}$, allowing X-ray photons to be sampled with a QE of approximately 100%. The SiLi crystal is cooled during operation to suppress the dark current by thermal conduction with liquid nitrogen that is stored in a 3.8 Lt Dewar. This prohibits the SiLi detector from being moved and was therefore permanently fixed to a vacuum flange with the CCD assembly mounted next to it. The internal face of the flange, sealed within the vacuum chamber, is shown in Figure 1.

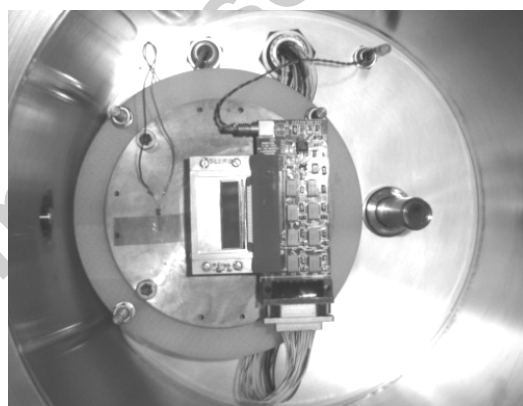


Fig. 1. CCD247 and SiLi detector mounted on the vacuum flange

The X-ray beam was design to be easily translated between the two fixed detectors, ensuring identical spatial displacement of the beam from the detectors with minimal temporal disruption between measurements; a bellows was used to maintain the vacuum as shown in Figure 2.

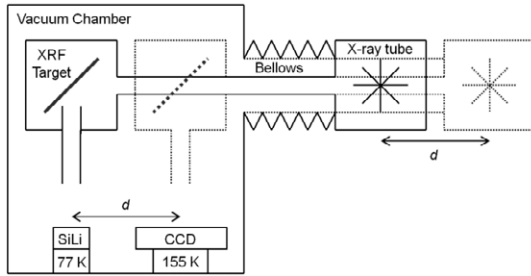


Fig. 2. The translatable X-ray fluorescence beam schematic

The fluorescence target material of the movable X-ray source can be substituted between experiments to acquire data for QE measurements at different photon energies.

3. Method

Characteristic X-rays were collimated with a steel collimator into a 50 mm² spot that could be translated across the horizontal plane of the CCD and SiLi detector. The X-ray source was initially aligned to the CCD and clamped into place. Images were acquired in continuous, full-frame mode, with zero additional integration between rows/frames. After acquisition of the CCD image, the X-ray source was immediately repositioned to align with the SiLi detector entrance window, within 5 seconds. This ensured that both detector measurements could be made within a source stability of 5%. A corresponding SiLi spectrum was then acquired for the X-ray beam for the same integration period as the CCD image. A number of CCD images and corresponding SiLi spectrums were obtained to increase the photon statistics for each of the X-ray energies measured.

The CCD pixel values were histogrammed and plotted as a spectrum. The energy scale was obtained by calibration to the background distribution and a known X-ray peak, typically the Fe-K α (6,403 eV) peak prevalent in all acquisitions due to fluorescence from the steel collimator. A background threshold was set to 6 σ above the peak of the Gaussian fitted to the background distribution to facilitate event recognition algorithms. Each split-pixel X-ray event

generated in the image was then processed to determine the photons incident energy, equivalent to the charge being collected entirely within 1 pixel (isolated). A second histogram of the CCD image was then produced for isolated events only; this was used to select the $\pm 3\sigma$ boundaries of the photon energy of interest. The cumulative count between these two boundaries was found and used to determine the detected X-ray flux at that energy. The silicon escape and pile-up peak energies were also calculated to $\pm 3\sigma$ and added to this count where possible. The total photon count in the CCD image at the selected energy was then normalised into counts.cm⁻².s⁻¹.

The spectral data acquired from the SiLi was similarly histogrammed to establish the total photon count at particular X-ray energies. Total counts in the SiLi spectrum for the energy selected were again normalised into counts.cm⁻².s⁻¹.

Flux calculated at the CCD was then divided by that obtained from the corresponding SiLi spectrum to calculate the relative QE. This was then multiplied by the modelled SiLi QE at that energy to determine an absolute CCD QE for the selected energy.

4. Results

4.1. Front Illuminated (FI) CCD247

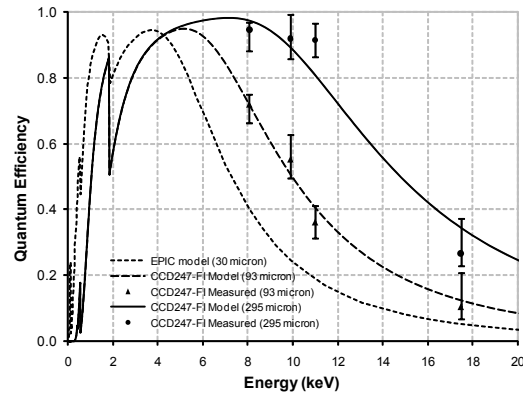


Fig. 3. QE measurements of the CCD247-FI

The measured QE data points for the CCD247-FI, shown in Figure 3, agree with the models for

depletion depths of 93 μm and 295 μm , when applying substrate potentials of 0 V and -110 V respectively, to within the estimated error of 9.6%. This error is estimated from the variation in output of the X-ray tube over the measurement time, the uncertainty of the SiLi detector measurements due to photon absorption in the entrance window and the incorrect measurement of pile-up and silicon-escape events in the CCD image.

The extra thickness of depletion that is achievable with high resistivity devices, such as the CCD247, allows adequate photon statistics to measure the QE at Mo-K α (17,478 eV). Only high energy (>8 keV) measurements have been taken at this time as the front-face illuminated device has not been optimised for low energy performance.

4.2. Back Illuminated (BI) CCD217

The back-face illuminated CCD217 [2] should have the greatest low energy QE of all the devices and this is supported by the data point at 2,308 eV shown in Figure 4. Nearly all of the data points are lower than expected for both the back and front-face illuminated device. This was attributed to the low responsivity of these first generation high resistivity devices, impacting on the event reconstruction, under-calculating the flux.

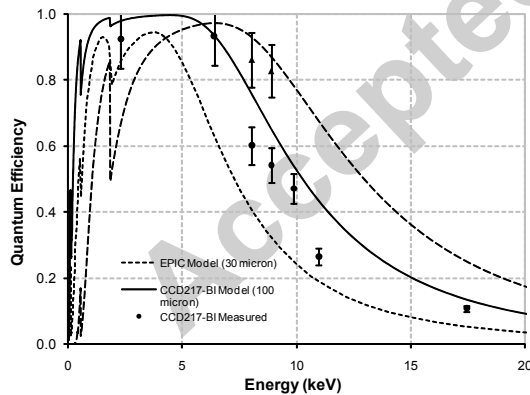


Fig. 4. QE measurements of the back illuminated CCD217

4.3. Swept-Charge Device (CCD54-FI)

The swept-charge device (SCD) [4] has a standard 3-phase electrode structure and therefore has reduced QE in comparison to the EPIC-MOS device [5]. Having a slightly thicker depletion region, the QE measurements for the SCD support a theoretical depletion depth of $\sim 40 \mu\text{m}$. The results shown in Figure 5 were obtained at -40°C .

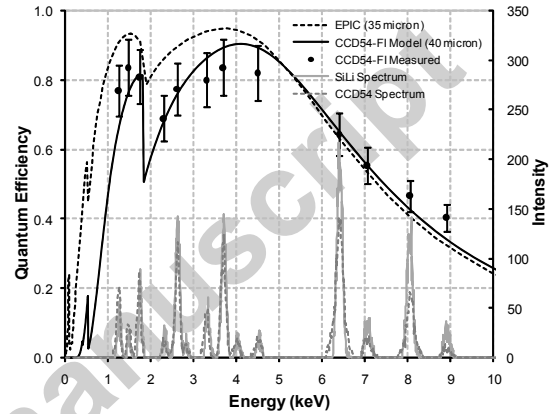


Fig. 5. QE measurements of the CCD54-FI (swept-charge device)

5. Conclusions

Quantum efficiency measurements of X-ray photons were taken about the centre of the CCD imaging areas using the QE facility developed to within a maximum error of 9.6% (<10% was desired).

Data points were plotted alongside the modelled QE curve for the CCD247 that was assumed to have been fabricated on 8 k Ω cm bulk p-type silicon. Due to the similarity between the data points and the model, a device depletion of 93 μm and 295 μm is believed for the CCD247-FI, when substrate potentials of 0 V and -100 V are applied respectively.

The CCD247-FI shows an improvement in QE for the higher energies (>4 keV), with an increase of $\sim 70\%$ at 10 keV compared to that of the EPIC-MOS devices onboard XMM-Newton, demonstrating the suitability of high-resistivity bulk silicon technology in future CCD based X-ray missions.

6. Future Work

The experimental downtime (~3.5 hours), experienced whilst changing the XRF target, could be significantly reduced by replacing the target box with one that includes a rotational target wheel, allowing multiple XRF targets to be positioned into the beam. The target wheel could not be rotated by a traditional vacuum feed-through due to the translation of the target box assembly during operation. Therefore, a stepper motor unit would be required to sit inside the target box and rotate the wheel between samples when required.

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